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Evolution of groundwater recharge-discharge balance in the Turpan Basin of China during 1959–2021

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Abstract: Groundwater overexploitation is a serious problem in the Turpan Basin, Xinjiang Uygur Autonomous Region of China, causing groundwater level declines and ecological and environmental problems such as the desiccation of karez wells and the shrinkage of lakes. Based on historical groundwater data and field survey data from 1959 to 2021, we comprehensively studied the evolution of groundwater recharge and discharge terms in the Turpan Basin using the groundwater equilibrium method, mathematical statistics, and GIS spatial analysis. The reasons for groundwater overexploitation were also discussed. The results indicated that groundwater recharge increased from 14.58×10^8 m^3 in 1959 to 15.69×10^8 m^3 in 1980, then continued to decrease to 6.77×10^8 m^3 in 2021. Groundwater discharge increased from 14.49×10^8 m^3 in 1959 to 16.02×10^8 m^3 in 1989, while continued to decrease to 9.97×10^8 m^3 in 2021. Since 1980, groundwater recharge-discharge balance has been broken, the decrease rate of groundwater recharge exceeded that of groundwater discharge and groundwater recharge was always lower than groundwater discharge, showing in a negative equilibrium, which caused the continuous decrease in groundwater level in the Turpan Basin. From 1980 to 2002, groundwater overexploitation increased rapidly, peaking from 2003 to 2011 with an average overexploitation rate of 4.79×10^8 m^3/a; then, it slowed slightly from 2012 to 2021, and the cumulative groundwater overexploitation was 99.21×10^8 m^3 during 1980–2021. This research can provide a scientific foundation for the restoration and sustainable use of groundwater in the overexploited areas of the Turpan Basin.

Keywords: groundwater overexploitation; groundwater recharge; groundwater discharge; climate change; human activities; Turpan Basin

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1 Introduction

Groundwater is not only an important component of water resources, but also plays a vital role in resource security (Pradeep and Krishan, 2022), ecological maintenance (Ren et al., 2018), and geological security (Li et al., 2018; Li et al., 2022a). Climate change and human activities have caused changes in groundwater resources in some regions in recent years, including serious problems such as overexploitation and pollution (Chen et al., 2020a; Chen et al., 2020b; Ding et al., 2020), which affect regional water security (Cha et al., 2018), ecological security (Mohallel and Gomaa, 2017; Wei et al., 2023), and geological security (Sheng, 2013). Therefore, determining the evolution of groundwater resources is necessary to promote the management and protection of groundwater resources and ensure water, ecological, and geological safety. Because

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of the importance of groundwater resources, theoretical and practical research has been conducted, especially in light of current problems such as increasingly significant climate change (Secci et al., 2022; Trásy-Havril et al., 2022), intense human activities (Mao et al., 2022), and their effects, e.g., rapid land use changes (Amini and Hesami, 2017; Kronvang et al., 2020; Warku et al., 2022). These problems have an important impact on the dynamic balance and recharge mechanism of groundwater, bringing the evolution of groundwater recharge to the forefront of scientific research (Sun et al., 2021; Adhikari et al., 2022; Duque and Rosenberry, 2022).

The evolution of groundwater has been studied in depth (Li et al., 2014; Li et al., 2022b). Both precipitation and exploitation impact the evolution of groundwater flow field, although exploitation has a stronger impact than precipitation (Feng et al., 2014). The groundwater drawdown funnel's growth rate accelerates as groundwater extraction increases. Groundwater level in the funnel tends to stabilize or rise as groundwater extraction stabilizes or declines (Shi et al., 2014). Wu et al. (2016) pointed out that human activities are the key factor influencing the evolution of groundwater recharge; nevertheless, the impact of climate change can be negligible. The development of an agro-ecosystem is directly related to changes in groundwater storage and water quality over time (Scanlon et al., 2010). The primary cause of regional groundwater level decline is agricultural irrigation, and groundwater level decline can be effectively avoided by reducing agricultural water use (Le Brocque et al., 2018). Although previous research has conducted in-depth analysis on one or several characteristic elements of groundwater in a certain area, there are few studies on the long-term, multi-element quantitative analysis of the evolution of groundwater recharge-discharge balance.

Turpan Basin is the first groundwater overexploited region identified in Xinjiang Uygur Autonomous Region of China and remains in overexploitation today. Continuous high intensity exploitation of groundwater is the main reason for groundwater overexploitation, according to qualitative and semi-quantitative research on the sustainable exploitation of groundwater resources in the Turpan Basin (Wang and Li, 1997; Chen, 2014; Abdisalam and Shi, 2015), as well as the influencing factors of the dynamic characteristics of groundwater level (Shang et al., 2020; Wu et al., 2021). At present, there are no objective and comprehensive reports on the evolution of groundwater in the Turpan Basin based on quantitative data. Specifically, this study investigated the evolution of seven groundwater recharge terms and six groundwater discharge terms to explore the recharge-discharge balance and its influencing factors, and revealed the causes of groundwater overexploitation in the Turpan Basin. This study can provide scientific basis for the sustainable development and utilization management of groundwater overexploited areas in the Turpan Basin.

2 Materials and methods

2.1 Study area

The Turpan Basin is located in the eastern part of Xinjiang Uygur Autonomous Region, China, at longitude of 87°06′–91°55′E and latitude of 41°12′–43°40′N. The administrative area includes the Gaochang District of Turpan City, Shanshan County, and Toksun County (Fig. 1). The Turpan Basin is a fully enclosed basin; it is surrounded by mountains to the north, west, and south, and is separated from the Hami Basin by hills to the east. The Yanshan and Huoyanshan mountains cross the centre of the basin from west to east, dividing the plain area into two sub-basins: the north basin and the south basin. At the centre of the Turpan Basin is the Aiding Lake, with a lake surface elevation of –154 m; it marks the lowest inland point in China. This study covers the Turpan Basin's artificial oasis plain region, including 4921.52 km^2 area in the north basin and 5954.79 km^2 area in the south basin.

Because of its unique geographical location and topography, the Turpan Basin has a warm arid climate typical of temperate continental deserts, with high temperatures and little precipitation. The annual average temperature at the centre of the basin is 14.00°C and the average annual

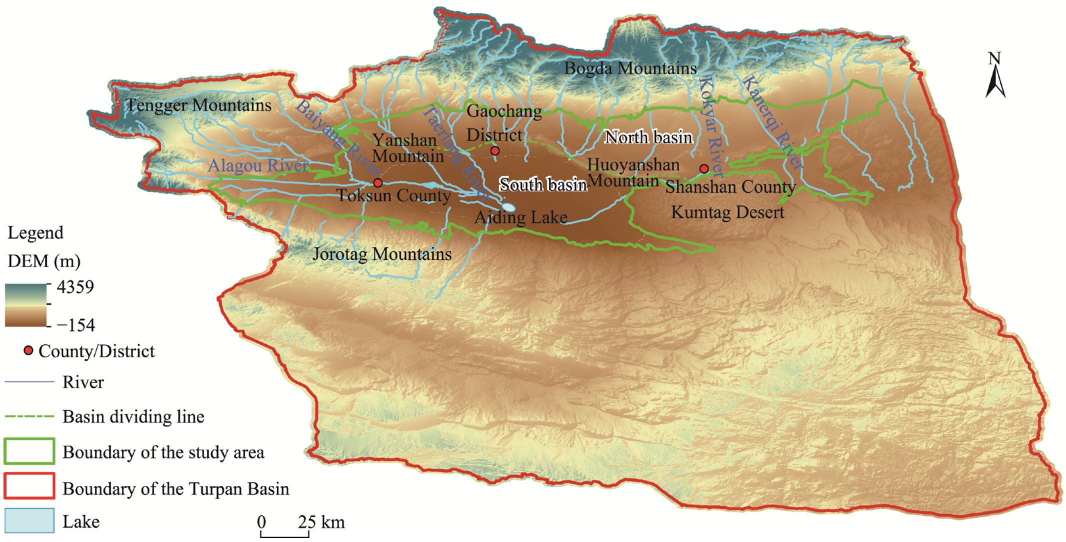

Fig. 1 Overview of the Turpan Basin and the location of the study area. DEM, digital elevation model.

precipitation is 16.40 mm. The water system of the Turpan Basin originates from the middle and high mountains in the west and north. The water recharge sources are ice and snow meltwater and mountain precipitation; surface runoff flows from the mountains to the plain area and finally into the Aiding Lake located at the centre of the basin. Fourteen large and small rivers are developed in the basin, with an average annual runoff of 8.95×10^8 m^3 (Wang et al., 2010). Among them, nine rivers with an average annual runoff of 6.74×10^8 m^3 belong to the Bogda Mountains system, three rivers with an average annual runoff of 2.00×10^8 m^3 belong to the Tengger Mountains system, and two rivers with an average annual runoff of 0.21×10^8 m^3 belong to the Jorotag Mountains system.

The thickness of the unconsolidated Fourth Series rocks in the Turpan Basin is 150–400 m, and the thickness of the Fourth Series in the local section west of Toksun County exceeds 500 m; thus, they provide sufficient storage space for groundwater. The north basin is a gravelly plain with a single diving aquifer structure, and the lithology of the aquifer is mainly pebbles and gravel. In the southern part of Shenjin and Qiktai townships in Shanshan County, a fine soil plain appears with double and multilayered structures, consisting of diving and pressurised aquifers; the lithology of the aquifer is mainly medium and coarse sands and gravels. The south basin is surrounded by a gravelly plain with a single submerged aquifer structure, and the central part of this basin is a fine soil plain with double and multilayered structures, consisting of submerged and confined aquifers; the lithology of the aquifer is mainly medium and fine sands and silt. The direction of groundwater runoff generally follows the topographic slope, from north to south in the north basin and from the surrounding area to the Aiding Lake in the south basin. Most of groundwater in the Turpan Basin is connected hydraulically through three gullies cutting the Huoyanshan Mountain, and the lateral outflow in the north basin is part of the lateral recharge in the south basin. The intra-annual and inter-annual dynamics of groundwater level in the basin are typical of artificial exploitation, and the inter-annual dynamics have been declining continuously since 1980, when the cumulative decline exceeded 50.0 m in some areas.

2.2 Data sources

Groundwater recharge in the plain area of the Turpan Basin includes the mountain front's lateral infiltration recharge (Q_{MFLIR}; 10^8 m^3/a), latent river flow recharge (Q_{LRFR}; 10^8 m^3/a), river infiltration recharge (Q_{RIR}; 10^8 m^3/a), canal leakage recharge (Q_{CLR}; 10^8 m^3/a), reservoir and pond seepage recharge (Q_{RPSR}; 10^8 m^3/a), and field infiltration recharge (Q_{FIR}; 10^8 m^3/a). The recharge terms of groundwater transformation (Q_{RETURN}; 10^8 m^3/a) include mechanical well extraction

(Q_{MW}; 10^8 m^3/a), karez well outflow (Q_K; 10^8 m^3/a), spring overflow (Q_S; 10^8 m^3/a), and artesian well outflow (Q_{AW}; 10^8 m^3/a). Because very few regions in the plain area of the Turpan Basin receive more than 10.00 mm of precipitation annually, the precipitation infiltration recharge can be ignored. Q_K, Q_S, river discharge (Q_R; 10^8 m^3/a), Q_{AW}, Q_{MW}, and evapotranspiration (Q_E; 10^8 m^3/a) are the principal groundwater discharge terms in the Turpan Basin.

All groundwater-related research results for the Turpan Basin since 1959 were comprehensively analyzed in this study. These results can be divided into five periods on a time scale. First, the "Report on Hydrogeological Conditions and Water Resources Development and Utilization in the Turpan Basin" was completed by the First Brigade of Hydrogeology, Xinjiang Bureau Geo-exploration & Mineral Development in 1963 (Li et al., 1963); its status quo year is 1959. Second, results during this period were from the "Comprehensive Assessment of Turpan Basin Water Resources 1/200,000" (Huang et al., 1990) and the "Research Report on the Efficient Use and Development of Groundwater in the Turpan Basin" (Cui et al., 1990), and the status quo year is 1989. Third, the "Research Report on Sustainable Utilization of Groundwater Resources in the Turpan Basin" (Yoshihisa, 2004) (current year of 2003) was completed in 2005 by the Japan International Industry Corporation. Fourth, the "Report on Groundwater Exploration in the Turpan Basin" was completed in 2013 by the First Brigade of Hydrogeology, Xinjiang Bureau Geo-exploration & Mineral Development (Zhang et al., 2013), and the status quo year is 2011. Fifth, the status quo year of this study (Qin et al., 2021) is 2021, and the survey was conducted in June 2021. This research quantitatively examined groundwater recharge and discharge terms as well as the dynamics of groundwater recharge-discharge balance in the Turpan Basin during 1959–2021 using the data obtained in the above mentioned five periods.

The Turpan Prefecture Bureau of Hydrology and Water Resources constructed 37 monitoring wells in 1985 to form groundwater monitoring system in the Turpan Basin. In 2017, 33 new groundwater level monitoring wells under state control were installed. This study extensively used the long-term groundwater level monitoring data from all 70 monitoring wells to validate the calculation data of groundwater overexploitation.

Furthermore, the formulas used in the calculation process were taken from Zhou et al. (2007), and the parameters were primarily based on the findings of this research experiment or referred to the study of Dong and Deng (2005), as well as the survey data obtained in June 2021.

2.3 Data analysis

2.3.1 Methods for processing series data

We analyzed the groundwater recharge and discharge information derived from the groundwater balance information in the five periods. The evolution of groundwater recharge and discharge terms and recharge-discharge balance was mainly studied using mathematical statistics and GIS spatial analysis. The baseline year was 1959, with 1989, 2003, 2011, and 2021 as the reference years. The data before 2021 were directly referred to the previous research results. The groundwater balance method was mostly employed to process the survey data in 2021, and the following data calculation methods were also used. We further used Excel 2016 to perform the analysis and ArcGIS 10.2 to draw the figures.

2.3.2 Calculation of the survey data

(1) Groundwater recharge calculation

Q_{MFLIR} and Q_{LRFR} were calculated using the Darcy formula:

$$Q_{MFLIR/LRFR} = K \times I \times M \times L \times 365 \times \sin a\ , \tag{1}$$

where $Q_{MFLIR/LRFR}$ represents the Q_{MFLIR} or Q_{LRFR} (10^8 m^3/a); K is the aquifer permeability coefficient (m/d); I is the groundwater hydraulic gradient (‰); M is the average thickness of the aquifer at the calculated section (m); L is the length of the calculated section (m); and a is the angle between the calculated section and the groundwater flow direction (°).

Q_{RIR} was determined as:

$$Q_{RIR} = Q_{up} + Q_{sink} - Q_{divert} - Q_{evaporation} - Q_{eiz}\ , \tag{2}$$

where Q_{up} is the measured runoff volume at the upstream hydrographic section of the river (10^8 m^3/a); Q_{sink} is the volume of water that enters the river (10^8 m^3/a); Q_{divert} is the volume of water diverted from the irrigated area between the upstream and downstream hydrographical sections of the river (10^8 m^3/a); $Q_{evaporation}$ is the evaporation from the river surface between the upstream and downstream hydrographical sections of the river (10^8 m^3/a); and Q_{eiz} is the evaporation from the infiltration zone between the upstream and downstream hydrographical sections of the river on both sides of the river channel (10^8 m^3/a). It should be noted that Q_{eiz} was negligible in the Turpan Basin, because most river channels are wide and shallow.

Q_{CLR} was calculated as:

$$Q_{CLR} = Q_{diversion1} \times \gamma' \times \gamma'' \times (1-\eta), \tag{3}$$

where $Q_{diversion1}$ is the average multiyear diversion of the canal system (10^8 m^3/a); γ' is the canal leakage correction coefficient; γ'' is the canal impermeability correction coefficient; and η is the effective utilization coefficient of the canal system.

Q_{FIR} was calculated as:

$$Q_{FIR} = Q_{diversion2} \times \beta, \tag{4}$$

where $Q_{diversion2}$ is the field irrigation diversion (10^8 m^3/a); and β is the field infiltration recharge coefficient.

Q_{RPSR} was determined as:

$$Q_{RPSR} = Q_{vrp} \times a_1, \tag{5}$$

where Q_{vrp} is the volume of the reservoir and pond (10^8 m^3/a); and a_1 is the seepage recharge coefficient of the reservoir and pond.

The calculation of Q_{RETUR} was similar to that of Q_{FIR}. First, the agricultural irrigation wells, karez wells, springs, and artesian wells in use were counted, and the infiltration recharge coefficient was selected on the basis of the buried groundwater level in the irrigated area. Next, the infiltration recharge of groundwater for irrigation was calculated in the field, as follows:

$$Q_{RETRRN} = Q_{SGW} \times a_2, \tag{6}$$

where Q_{SGW} is the sum of the groundwater used by mechanical wells, karez wells, springs, and artesian wells (10^8 m^3/a); and a_2 is the groundwater return infiltration coefficient, which has an empirical value depending on the study area.

(2) Groundwater discharge calculation

The amounts of Q_K, Q_S, Q_{AW}, Q_{MW}, and Q_R were based on the survey data obtained in June 2021. Q_E was classified into irrigated groundwater evapotranspiration excretion (Q_{Ecg}; 10^8 m^3/a) and non-irrigated groundwater evapotranspiration excretion (Q_{Eng}; 10^8 m^3/a).

$$Q_E = Q_{Ecg} + Q_{Eng}. \tag{7}$$

Q_{Ecg} was calculated as:

$$Q_{Ecg} = 10^{-5} \times E_{601} \times C \times F \times \left(C' \times \frac{E_{601.1}}{E_{601}} - \frac{E_{601.1}}{E_{601}} \right), \tag{8}$$

where E_{601} is the annual water surface evaporation (mm); C is the groundwater evaporation coefficient; F is the area of the calculation region (km^2); C' is a correction coefficient, depending on the evaporation from vegetation under crop cover conditions (the cover rate was taken as 90%); and $E_{601.1}$ is the water surface evaporation during crop growth and maturation period from April to September (mm).

Q_{Eng} was determined as:

$$Q_{Eng} = 10^{-5} \times E_{601} \times C \times F \times (C''+1), \tag{9}$$

where C'' is a correction coefficient for evaporation from vegetation under vegetation cover conditions.

(3) Calculation of cumulative groundwater storage variables

The following equation was used to determine cumulative groundwater storage variables (ΔW;

10^8 m^3/a):

$$\Delta W = 10^{-2} \times \mu \times (h_1 - h_2) \times A / \Delta t , \tag{10}$$

where μ is the aquifer feeding degree in the groundwater change zone of the calculation area; h_1 is the groundwater level at the beginning of the calculation period (m); h_2 is the groundwater level at the end of the calculation period (m); A is the area of the groundwater level variation zone (km^2); and Δt is the groundwater equilibrium calculation period (a).

3 Results

3.1 Evolution of groundwater recharge

Groundwater recharge in the Turpan Basin from 1959 to 2021 is shown in Figure 2 and Table 1. The mode, process, and intensity of groundwater recharge changed significantly; primarily, surface water conversion recharge altered significantly, whereas natural recharge did not changed significantly.

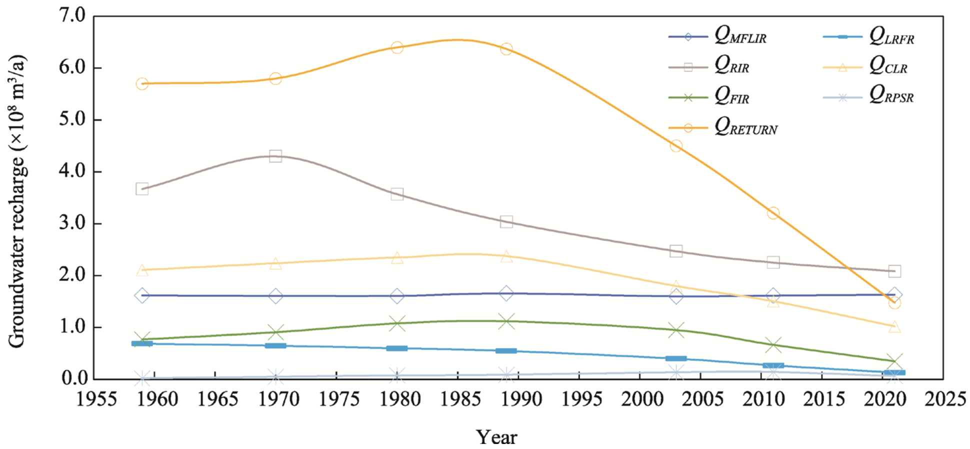

Fig. 2 Evolution of seven groundwater recharge terms in the Turpan Basin during 1959–2021. Q_{MFLIR}, mountain front's lateral infiltration recharge; Q_{LRFR}, latent river flow recharge; Q_{RIR}, river infiltration recharge; Q_{CLR}, canal leakage recharge; Q_{FIR}, field infiltration recharge; Q_{RPSR}, reservoir and pond seepage recharge; Q_{RETURN}, recharge terms of groundwater transformation.

Table 1 Groundwater recharge and discharge data in the Turpan Basin in the five periods of 1959, 1989, 2003, 2011, and 2021

Year	Groundwater recharge (×10^8 m^3/a)								Groundwater discharge (×10^8 m^3/a)						
	Q_{MFLIR}	Q_{LRFR}	Q_{RIR}	Q_{CLR}	Q_{FIR}	Q_{RPSR}	Q_{RETURN}	Total	Q_E	Q_R	Q_K	Q_{MW}	Q_S	Q_{AW}	Total
1959	1.62	0.69	3.67	2.11	0.77	0.02	5.70	14.58	5.16	0.71	5.78	0.01	2.83	0.00	14.49
1989	1.66	0.55	3.04	2.38	1.12	0.09	6.37	15.20	3.72	0.57	3.70	4.88	2.68	0.47	16.02
2003	1.60	0.40	2.47	1.80	0.95	0.14	4.50	11.86	3.30	0.35	2.70	6.40	1.96	0.26	14.97
2011	1.62	0.27	2.25	1.51	0.67	0.14	3.21	9.66	2.37	0.28	1.35	8.28	1.57	0.09	13.95
2021	1.63	0.13	2.08	1.02	0.35	0.07	1.48	6.77	1.47	0.00	0.91	6.71	0.88	0.00	9.97

Note: Q_{MFLIR}, mountain front's lateral infiltration recharge; Q_{LRFR}, latent river flow recharge; Q_{RIR}, river infiltration recharge; Q_{CLR}, canal leakage recharge; Q_{FIR}, field infiltration recharge; Q_{RPSR}, reservoir and pond seepage recharge; Q_{RETURN}, recharge terms of groundwater transformation; Q_E, evapotranspiration; Q_R, river discharge; Q_K, karez well outflow; Q_{MW}, mechanical well extraction; Q_S, spring overflow; Q_{AW}, artesian well outflow.

Q_{MFLIR} was approximately 1.60×10^8 m^3/a, which essentially remained unchanged, owing to consistent precipitation and river runoff in recent years with a minor rising tendency.

Natural Q_{LRFR} was 0.69×10^8 m^3/a. Specifically, before 1980, development was slow and few reservoirs were built. However, after 1980, with the acceleration of reform, 12 mountain

reservoirs were built in the basin, such as Ertanggou, Kekeya, and Kanerqi. Because the impermeability of the dam base essentially cut off the submerged river flow, only a few smaller river gullies without mountain barrage reservoirs remained to be recharged by submerged river flow, which exhibited a slow decrease in Q_{LRFR} from 1959 to 1989 and a rapid decline in Q_{LRFR} from 1989 to 2021.

Q_{RIR} is affected by both river runoff and canal diversion. According to the hydrological data provided by the Turpan Prefecture Bureau of Hydrology and Water Resources, the runoff volume of the rivers in the basin was essentially stable during 1959–2021. However, since the 1990s, control reservoirs and barrage headworks have been built to regulate surface water, changing the process and volume of river runoff. Consequently, supporting channel diversions increased and river overflow decreased. Q_{RIR} showed a pattern consistent with Q_{LRFR}: a slow decrease from 1959 to 1989 and a rapid decrease from 1989 to 2021.

Changes in the seepage recharge of the canal system are related mainly to the amount of diversion and canal impermeability. Since 1960, diversion trunk and branch canals have been under construction in the basin, and the diversion volume has increased continuously. In 1980, the construction of canals was shifted to increase the lining rate simultaneously. Therefore, Q_{CLR} showed a slow increase from 1959 to 1989, followed by a rapid decrease from 1989 to 2021.

The variation in Q_{FIR} is related mainly to the amount of field diversion, irrigation methods, and the depth of groundwater level in the irrigated area. The amount of Q_{FIR} increased continuously before 1990, and then essentially stable. Before 1980, most of the basin was irrigated with large amounts of water. In 2000, the conventional field water-saving irrigation methods, such as border irrigation and fine-flow furrow irrigation, were popularized in the basin. After 2005, advanced drip irrigation and other advanced water-saving technologies started to be introduced and promoted. The depth of groundwater level in the irrigated area of the basin remained stable until 1980 and declined continuously thereafter. Generally speaking, Q_{FIR} increased from 1959 to 1989 while decreased from 1989 to 2021.

Q_{RPSR} includes the seepage recharge of water reservoirs and ponds in the plain area. Before 2011, with increasing water diversion, several water reservoirs and ponds were built in the basin, resulting in the increase of infiltration. After 2011, the seepage gradually decreased with the completion of de-risking and the development of various water storage projects. Therefore, Q_{RPSR} increased from 1959 to 2011, then decreased until 2021.

Q_{RETURN} was 5.70×10^8 m^3 in 1959, increased to 6.40×10^8 m^3 in 1980, and remained nearly constant from 1980 to 1990. Then, Q_{RETURN} decreased rapidly from 1990 to 2021, at a value of 1.48×10^8 m^3 in 2021. The main reason is the rapid decrease in groundwater outflow, which caused the canal and field water utilization coefficients to increase gradually and the depth of groundwater level to decrease.

3.2 Evolution of groundwater discharge

Results of groundwater discharge terms in the Turpan Basin from 1959 to 2021 are shown in Table 1. During 1959–2021, groundwater outflow in the Turpan Basin showed a significant change due to the decline in groundwater level.

We analyzed the number of karez wells and Q_K for nine periods: 1959, 1959, 1987, 1990, 1994, 2004, 2011, 2014, and 2021 (Fig. 3). From 1959 to 1987, the number of karez wells and the value of Q_K decreased slowly first and then decreased more rapidly before exhibiting a slow decrease. During 1957–1987, the number of karez wells decreased at an average rate of 10 bars/a, and Q_K decreased at a rate of 0.06×10^8 m^3/a. From 1987 to 2011, the number of karez wells decreased most rapidly, with an average rate of 30 bars/a, and Q_K decreased at a rate of 0.12×10^8 m^3/a. From 2011 to 2021, the decreasing rate of the number of karez wells slowed gradually, with an average rate of 7 bars/a, and Q_K decreased at a rate of 0.05×10^8 m^3/a. It is known from the principle of karez wells (Deng, 2010) that the continuous decline in groundwater level is the leading cause of the drying up and flow decay of karez wells.

The available information shows that the mechanical wells in the Turpan Basin were primarily

established in 1960. Q_{MW} in the Turpan Basin exhibited distinct behaviours in different periods (Fig. 4). First, slow growth in Q_{MW} occurred from 1960 to 1980. In 1960, the Turpan Basin had 16 mechanical wells, with a total Q_{MW} value of 0.01×10^8 m^3. By 1980, 1058 mechanical wells existed, with a total Q_{MW} value of 1.82×10^8 m^3, an average annual increase number of 52 new mechanical wells, and an increase rate in Q_{MW} of 0.09×10^8 m^3/a. Second, a rapid growth in Q_{MW} occurred from 1980 to 1990, which coincides with the reform policy and land development. The number of mechanical wells increased, at an average annual increase number of 133 new mechanical wells and an increase rate in Q_{MW} of 0.31×10^8 m^3/a. Third, from 1990 to 2003, the increase rate of Q_{MW} decreased, with 81 new mechanical wells added each year. During this period, Q_{MW} increased by 0.12×10^8 m^3/a. Fourth, from 2003 to 2010, the number of new mechanical wells increased rapidly, with an average of 334 new mechanical wells added each year. Q_{MW} during this period increased by 0.31×10^8 m^3/a, reaching a peak of 8.60×10^8 m^3 in 2010. Fifth, in 2006, the Turpan Basin was designated as a groundwater overexploited area, and from 2010 to 2021, a series of groundwater control measures were introduced, beginning to limit the amount of Q_{MW}, shutting down some mechanical wells, and scrapping an average of 57 mechanical wells every year. Therefore, Q_{MW} during this period decreased at an average of 0.19×10^8 m^3/a, reaching up to 6.71×10^8 m^3 by 2021 (Fig. 4).

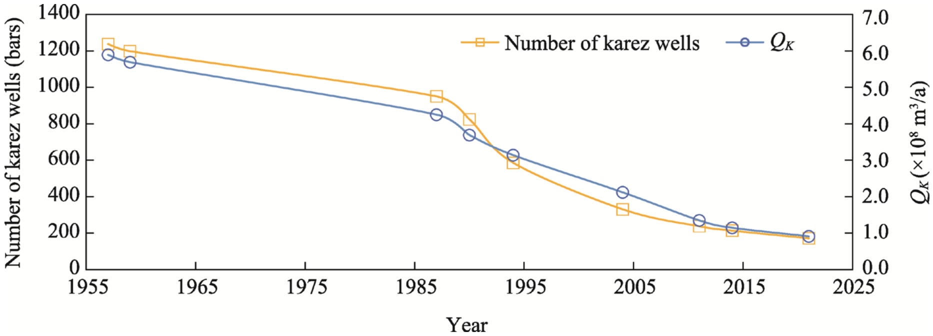

Fig. 3 Evolution of the number of karez wells and the amount of karez well outflow (Q_K) in the Turpan Basin during 1959–2021

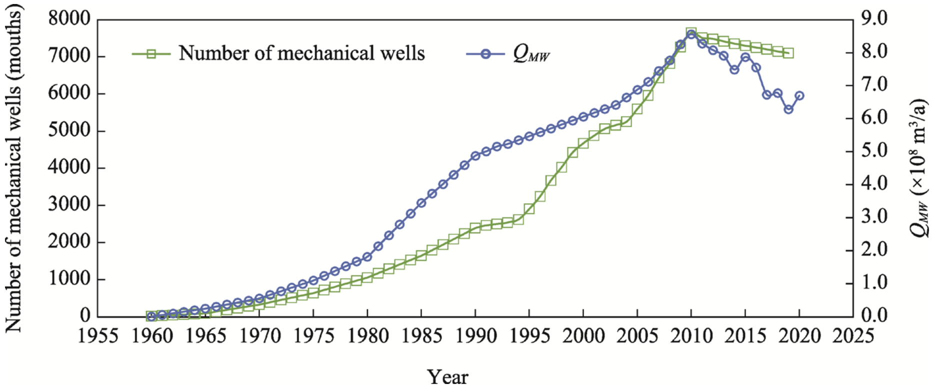

Fig. 4 Evolution of the number of mechanical wells and the amount of mechanical well extraction (Q_{MW}) in the Turpan Basin during 1959–2021

Artesian wells appear mainly in the south basin and the area north of the Huoyanshan Mountain. The number of artesian wells increased with the increase of mechanical wells. Q_{AW} also increased from 1970 to 1980 and remained stable at an average annual value of 0.47×10^8 m^3 during 1980–1989 (Fig. 5). After 1989, the number of mechanical wells continued to increase, and groundwater pressure in artesian wells decreased. Correspondingly, Q_{AW} also decreased continuously. No self-flowing behaviour was observed in artesian wells until the survey in June 2021.

Spring water in the Turpan Basin is concentrated mainly in the area north of the Huoyanshan Mountain. Q_S decreased very little between 1960 and 1989, and the decay rate of Q_S increased after 1989, with an average annual decay rate of 0.05×10^8 m^3 from 1990 to 2011 (Fig. 5). Further, from 2011 to 2021, the average annual decay rate of Q_S increased to 0.07×10^8 m^3. The continuous decrease in Q_S since 1989 was mainly caused by the continuous decline in groundwater level in the north of the Huoyanshan Mountain.

As shown in Figure 5, Q_R was essentially stable before 1980, at approximately 0.70×10^8 m^3/a, and decreased continuously after 1980 (Fig. 5). This phenomenon was not observed until the survey in June 2021, mainly because of the continuous decline in groundwater level. Q_E discharge is closely related to groundwater level and vegetation cover. It remained essentially stable from 1959 to 1980; after 1980, however, it decreased continuously, until 2021. The main reason is the continuous decline of groundwater level in areas above 6.0 m (the limit of groundwater evaporation and transpiration).

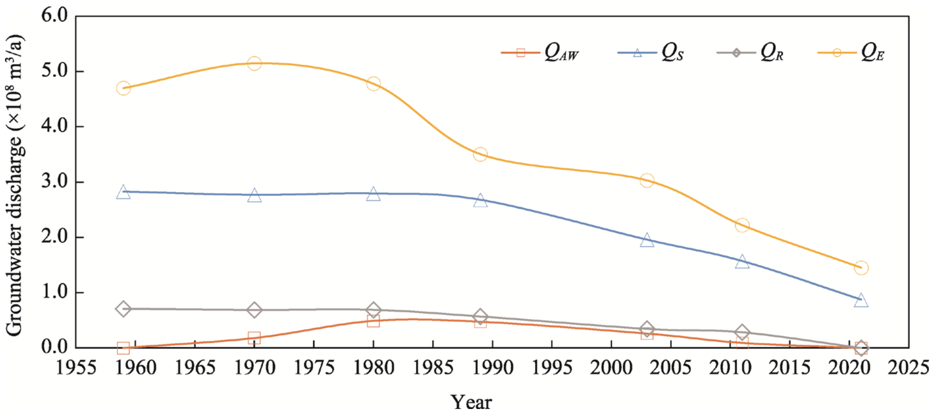

Fig. 5 Evolution of groundwater discharge terms in the Turpan Basin during 1959–2021. Q_{AW}, artesian well outflow; Q_S, spring overflow; Q_R, river discharge; Q_E; evapotranspiration.

3.3 Evolution of groundwater recharge-discharge balance

The evolution of groundwater recharge-discharge balance in the Turpan Basin since 1959 was obtained by summarizing various groundwater recharge and discharge terms, as shown in Figure 6. From 1959 to 1980, both groundwater recharge and discharge in the Turpan Basin showed a slightly increasing trend and then remained essentially in equilibrium. Since groundwater recharge-discharge balance was disrupted in 1980, the amount of discharge was always greater than that of recharge, indicating a negative equilibrium. From 1980 to 2021, the rate of groundwater overexploitation in the basin increased rapidly and then decreased slightly. Groundwater overexploitation rate was highest from 2003 to 2011, reaching 4.79×10^8 m^3/a, after which it began to decrease, consisting with the groundwater overexploitation zone management conducted after 2010 and the reduction in groundwater extraction. The cumulative groundwater overexploitation in the Turpan Basin from 1980 to 2021 was calculated to be 99.21×10^8 m^3, as shown in Table 2.

In addition, Figure 6 shows that groundwater recharge and discharge in the Turpan Basin indicated a continuous decrease after 1980. Groundwater recharge decreased from 15.69×10^8 m^3 in 1980 to 6.77×10^8 m^3 in 2021, a decrease of 56.85% (average decrease rate of 0.22×10^8 m^3/a). Groundwater discharge decreased from 15.66×10^8 m^3 in 1980 to 9.97×10^8 m^3 in 2021, a decrease of 36.33% (average decrease rate of 0.14×10^8 m^3/a). The rate of decrease in recharge was always greater than the rate of decrease in discharge, and the recharge volume was always lower than the discharge volume, indicating a negative equilibrium. This is the result of the continuous decline of groundwater level, and also the real objective cause of groundwater overexploitation in the Turpan Basin.

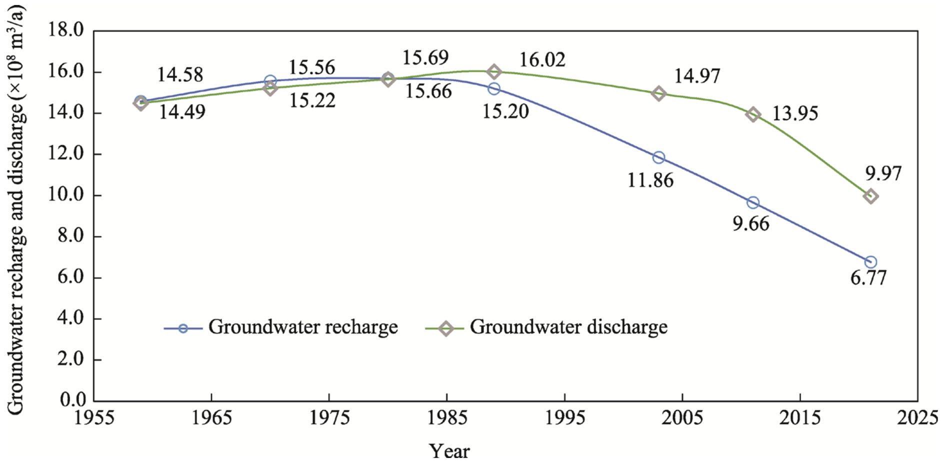

Fig. 6 Evolution of groundwater recharge and discharge in the Turpan Basin during 1959–2021

Table 2 Calculation of groundwater overexploitation in the Turpan Basin during 1959–2021

Period	End of period			Average overexploitation ($\times10^8$ m^3/a)	Cumulative overexploitation ($\times10^8$ m^3)
	Recharge ($\times10^8$ m^3/a)	Discharge ($\times10^8$ m^3/a)	Overexploitation ($\times10^8$ m^3/a)		
1959	14.58	14.49	-	-	-
1960–1970	15.56	15.22	-	-	-
1970–1980	15.69	15.66	-	-	-
1980–1989	15.20	16.02	0.82	0.36	3.21
1989–2003	11.86	14.97	3.11	1.40	19.57
2003–2011	9.66	13.95	4.29	4.79	38.35
2011–2021	6.77	9.97	3.20	4.23	38.08
Total					99.21

Note: There was no overexploitation before 1980, as indicated by the sign "-".

4 Discussion

4.1 Verification of groundwater overexploitation

Groundwater level in the Turpan Basin has been declining continuously since 1980. The decline can be divided into four stages on the basis of groundwater recharge-discharge balance shown in the previous sections and groundwater level monitoring data. Figure 7 shows the spatial distribution of groundwater level decline in each stage, and the details are described and analyzed as follows.

(1) During 1980–1989, the south basin showed a slow decline in groundwater level, mainly in Tuyuk, Darank, and Lukqin townships in Shanshan County, located in the south of the Huoyanshan Mountain. Because these areas took the lead in reclaiming wasteland and drilling wells, groundwater discharge in these areas is greater than groundwater recharge. Groundwater level in the whole basin first began to decline at rates varying from 0.1 to 0.4 m/a. As the areas of decline in groundwater level expanded, the annual decline rate gradually increased. For example, groundwater level in the irrigated area of the whole basin decreased at an average rate of 0.1 m/a.

(2) During the rapid decline phase from 1989 to 2003, the decline rate of groundwater level increased in most areas of the south basin, and the areas of decline in groundwater level extended from the region around Tuyuk Township of Shanshan County in the south of the Huoyanshan Mountain to the entire oasis plain in the south of Shanshan County. A groundwater level landing funnel was formed, with an overall average decline rate of 0.4 m/a, and the decline rate at the centre of the funnel has reached up to 2.7 m/a.

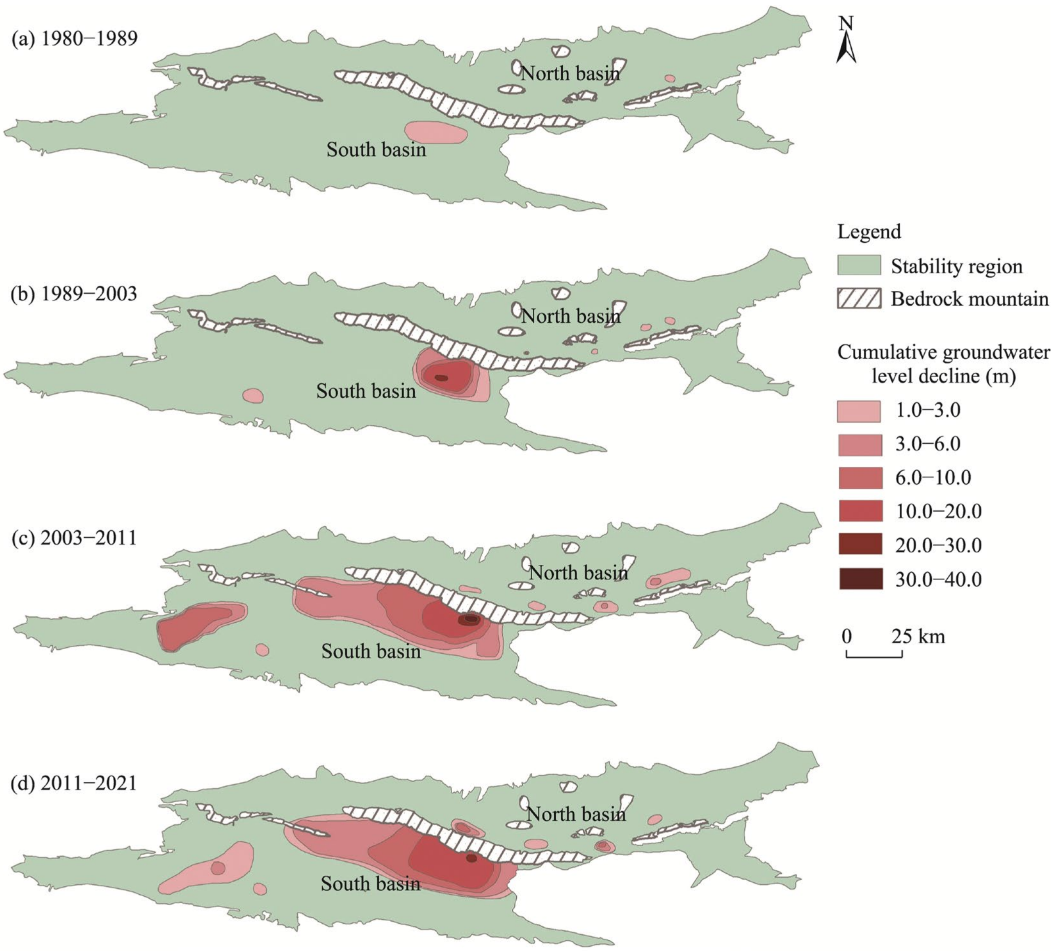

Fig. 7 Spatial distribution of cumulative groundwater level decline in the Turpan Basin during 1980–2021. (a), 1980–1989; (b), 1989–2003; (c), 2003–2011; (d), 2011–2021.

(3) During 2003–2011, the decline in groundwater level slowed in the north basin; by contrast, the entire south basin underwent rapid decline in groundwater level, showing an increase in the decline rate of groundwater level. The areas of decline in groundwater level extended from Shanshan County in the southern part of the Huoyanshan Mountain to the other areas in the south of the mountain, and from the east of the Yanshan Mountain to the western edge of the Kumtag Desert. The region also extended to the north of the Huoyanshan Mountain, i.e., in the areas from Qiktai Township to Shenjin Township in Shanshan County and the areas of Bostan, Yilahu, and Guolebuy townships in Toksun County. The average decline rate of groundwater level in the oasis plain was 1.1 m/a, and the decrease rate in Tuyuke Town was the highest (3.2 m/a), with a cumulative decline of 24.0 m.

(4) During 2011–2021, the basin-scale decline rate of groundwater level gradually decreased, and Turpan City began to control its groundwater overexploitation by reducing water use, sealing or filling mechanical wells, and reducing groundwater extraction. The trend of continuous decline in groundwater level in the periphery of the irrigated area near the mountain front was alleviated; however, the area with high-intensity mechanical well extraction of groundwater in the centre of the irrigated area still declined rapidly. Groundwater level in the basin-scale oasis plain area declined at an average rate of 1.0 m/a, and the rate of decline in the overexploited area of the south basin was even higher, averaging 1.2 m/a.

The cumulative groundwater storage during 1980–2021 was 102.10×10^8 m^3. Table 3 displays the computation results of groundwater storage variables for each time period. Annual

groundwater storage variables gradually increased from 1980 to 2011, then they began to decline from 2011 to 2021. The previous section calculated the cumulative groundwater overexploitation (99.21×10^8 m^3) during 1980–2021 through the balance of groundwater recharge and discharge, which is consistent with the cumulative groundwater storage variables (difference of 2.9%), so the calculated groundwater overexploitation in the Turpan Basin during 1980–2021 is relatively accurate and reliable.

Table 3 Groundwater storage variables in the Turpan Basin during 1980–2021

Period	Average annual groundwater storage variables ($\times10^8$ m^3/a)	Cumulative groundwater storage variables ($\times10^8$ m^3)
1980–1989	0.43	3.90
1989–2003	1.53	21.40
2003–2011	4.81	38.54
2011–2021	3.82	38.23
Sum	2.49	102.10

4.2 Primary causes of groundwater recharge and discharge evolution

Climate change and human activities are primarily driving the evolution of groundwater recharge-discharge balance. There has been a warming trend in the Turpan Basin since 1950, with an average temperature rise rate of 0.45°C/decade (Su et al., 2003; Ren and Yang, 2007; Alanur et al., 2019). Precipitation also showed a moderate rising tendency during 1959–2021, with an increase rate of approximately 1.61 mm/decade (Keranmu and Abudushalike, 2014; Shang et al., 2018; Yang et al., 2018). River runoff in the Turpan Basin was steady during 1959–2021, with a slightly increasing trend (Chen, 1998; Ye et al., 2014; Zhang et al., 2020). Precipitation and evaporation had little impact on groundwater level in arid areas (Ma et al., 2002; Wang et al., 2014; Shang et al., 2020), while human activities were the dominant factor influencing groundwater level.

The proportion of agricultural water use in the Turpan Basin was as high as 92.21%, and the continuous decline in groundwater level was caused by the expansion of the irrigated area and the advancement of irrigation methods, not by climate change or the single reason of increased groundwater extraction by mechanical wells. The river bed of the mountain reservoirs was blocked off, lowering the amount of latent river flow. Furthermore, as a result of water conservation initiatives, water flowed through channels instead of rivers, reducing river leakage. The seepage prevention rate of the canal system rose despite the increased canal water diversion, but the canal leakage dropped. Additionally, the seepage prevention rate of reservoirs and ponds was improved, and the seepage amount from reservoirs and ponds decreased. Finally, the area of cultivated land was expanded, effective water-saving technology was promoted, irrigation quota and the amount of field infiltration water were significantly decreased, and the amount of return water infiltration from mechanical wells, springs, and karez wells were also significantly reduced.

This finding contradicts the prior understanding that over-extraction of groundwater from wells, which was only quantitatively examined as one element in groundwater extraction from wells in terms of discharge volume, is the primary cause of overexploitation. This study was more objective, comprehensive, and scientific as it systematically analyzed seven groundwater recharge terms and six groundwater discharge terms. Currently, the penetration rate of efficient water-saving has reached up to 90% in the Turpan Basin. The water-saving opportunity is not obvious, and the existing water resources are unable to support the current irrigated area. To achieve balanced groundwater recharge and discharge, it is, therefore, necessary to significantly decrease the irrigated area or carry out industrial transformation, and reduce water consumption and the quantity of groundwater exploitation without resorting to external water sources. Then, the decline in groundwater level can be reversed.

5 Conclusions

In this study, the evolution of seven groundwater recharge terms and six discharge groundwater terms from 1959 to 2021 was used to analyzed groundwater recharge-discharge balance in several historical periods (1959, 1970, 1980, 1989, 2003, 2011, and 2021), and the reasons for the continuous overexploitation of groundwater were revealed. Additionally, we determined the extent of groundwater overexploitation and reached the following conclusions.

(1) From 1959 to 2021, groundwater recharge first increased slightly and then decreased continuously. The total groundwater recharge increased from 14.58×10^8 m^3 in 1959 to 15.69×10^8 m^3 in 1980 and then decreased to 6.77×10^8 m^3 by 2021.

(2) From 1959 to 2021, groundwater discharge showed a slight increase followed by a continuous decrease, increasing from 14.49×10^8 m^3 in 1959 to 16.02×10^8 m^3 in 1989 and then decreasing continuously to 9.97×10^8 m^3 in 2021.

(3) Groundwater recharge and discharge in the Turpan Basin were in equilibrium before 1980. Subsequently, from 1980 to 2021, groundwater recharge decreased by 56.85%, with an average decrease rate of 0.22×10^8 m^3/a, and groundwater discharge decreased by 36.33%, with an average decrease rate of 0.14×10^8 m^3/a. The rate of decrease in groundwater recharge was always greater than the rate of decrease in groundwater discharge, and the amount of groundwater recharge was always lower than the amount of groundwater discharge. This is the real objective cause of groundwater overexploitation in the Turpan Basin.

(4) From 1980 to 2021, groundwater storage decreased, and the decay rate initially accelerated and then decelerated, leading to a total overexploitation of 99.21×10^8 m^3.

The evolution of groundwater recharge-discharge balance in the Turpan Basin is explored in detail in this study, and our understanding of groundwater overexploitation is expanded. However, further improvement is required, and the impact of land and water resources utilization on groundwater should be considered in the future.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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